AQUATIC COMMUNITY RESPONSES TO STREAM RESTORATION:

EFFECTS OF WOOD AND SALMON ANALOG ADDITIONS

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Abstract

Many aquatic ecosystems in the Pacific Northwest have been impacted by land use activities. Often these impacts have resulted in deleterious effects that directly or indirectly limited the capacity of habitat to produce fish. Habitat restoration potentially increases the quantity and quality of resources available to the aquatic communities within these impaired systems, thus increasing biotic integrity and fish production.

In this study, responses of aquatic communities exposed to woody debris bundle and salmon analog additions were measured in the year following creation of off-channel, fish habitat in southcentral Alaska. Biofilm, invertebrates and juvenile coho salmon, *Oncorhynchus kisutch*, were sampled in four treatment types (control, wood, analog, and analog+wood). Biofilm significantly increased in analog enriched treatments. No treatment effects were detected in benthic invertebrate responses, however, treatment differences were detected in coho diets. Coho density and standing stock were significantly higher in the wood treatment, and coho in the control treatment showed signs of density-dependent limitations. Condition for fish was highest in the analog enriched treatments after treatment additions. These results suggest salmon analog and woody debris bundle additions may be viable short-term restoration tools, providing a boost in food and shelter for aquatic communities in habitats undergoing restoration.

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Introduction

Significant research effort in fisheries and stream ecology has focused on the impacts of land use on stream ecosystems (Cederholm et al. 1980; Hartman and Scrivener 1990; Nelson et al. 1991). Practices such as logging, road building or surface mining have been shown to negatively impact aquatic communities. These adverse effects often lead to unfavorable changes in how watersheds function biologically and structurally (NRC 1996). Land use activities can reduce woody debris abundance and increase fine sediment loading into streams, which can lead to loss of habitat complexity, increased nutrient export rates, low fish egg survival and decreased growth and survival rates of juvenile salmonids (Grette 1985; Platts et al. 1989; Reiser and White 1988; Smock et al. 1989; Suttle et al. 2004). In addition, in-stream mining practices for precious metals, sand, and gravel have left numerous watersheds across North America channelized, void of riparian or in-stream cover, and with increased levels of heavy metals (Nelson et al. 1991).

Due to the deleterious effects of past natural resource use, many native fish stocks have been impacted and stream restoration has become a critical component of conserving and restoring those stocks (Roni et al. 2002). Restoration practices can be used to return impacted streams to a more pre-disturbance condition, presumably enabling it to recover to a state of high biological integrity, where the stream can express its full range of natural variability (Kauffman et al. 1997; Williams et al. 1997; Frissell and Ralph 1998). Over the past few decades, methods to revert impacted streams to pre-disturbed status have become a focus of many federal, state, and non-profit organizations across the United States. Each year, millions of dollars are allocated to stream restoration projects in the Pacific Northwest alone to restore aquatic systems that were impaired as an indirect or direct result of human activity (NRC 1996). These efforts differ in scale, ranging from altering the features of an entire watershed to creating a few off-channel habitats (Weaver et al. 1987; Cederholm et al. 1988; Rosgen 1988; Platts et al. 1989; Richards et al. 1992).

Restoration projects have had varied success in the past and only limited research has evaluated the effectiveness of the assorted techniques (Reeves et al. 1991; Frissell and Nawa 1992; Roni et al. 2002). To be effective, restoration efforts should begin with an evaluation of what is limiting the aquatic community in an altered watershed. These limitations could include either density-dependent (e.g., space, cover, food) or density-independent (e.g., floods, droughts, landslides) factors. In cases where density-dependent factors are limiting foodwebs, adding nutrients and wood or creating more habitat could be effective restoration techniques (Achord et al. 2003). However, restoration efforts are unlikely to be successful if they do not address watershed-wide problems (e.g., altered stream geomorphology, lack of winter and flow refugia, or nonnative predators) that are possibly limiting the capacity of the stream to support its native and productive aquatic community. By using an experimental approach to restoration, biologists gain insight to both what is limiting the system that requires restoration and the effectiveness of the restoration strategy (i.e, adaptive management) (Williams et al. 1997).

Across Alaska and much of the Pacific Northwest, the addition of large and fine woody debris to degraded anadromous salmonid streams has become a common restoration tactic (Kauffman et al. 1997). Among other things, in-stream woody debris creates refugia for invertebrates and fish, and provides foraging habitat (Mundie 1969; Angermeier and Karr 1984; Fausch 1993; Reinhardt and Healey 1997). Historically, woody debris was removed from numerous coastal streams and rivers as a result of logging, mining and urbanization (Hicks et al. 1991). In an effort to reverse the problems created by the reduced densities of woody debris in streams, managers and researchers have added logs, root wads, and debris bundles, all of which attempt to mimic the effects of naturally occurring woody debris (Angermeier and Karr 1984). Additions such as these can result in increased invertebrate abundances, juvenile salmonid growth, winter survival, diversity, density, carrying capacity, and smolt output (Angermeier and Karr 1984; Gowan and Fausch 1996; Cederholm et al. 1997; Inoue and Nakano 1998; Solazzi et al. 2000; Giannico and Hinch 2003; Johnson et al. 2005).

Recent research has also illustrated the positive effects of marine-derived nutrients (MDN) from anadromous species in some freshwater ecosystems. When adult salmon return to freshwater each year to spawn and die, their carcasses deposit nitrogen, phosphorus, and energy-rich carbon compounds into streams that can be nutrient-limited (Mathisen et al. 1988; Wipfli et al. 1998). Due to the precipitously declining numbers of salmon returning to many watersheds of the Pacific Northwest, Gresh et al. (2000) speculated that these systems may be falling into a nutrient deficit. Consequently, these low concentrations of nutrients may limit the capacity of many coastal watersheds (Achord et al. 2003). However, case studies have shown that artificially adding nutrients to nutrient-limited systems can boost community productivity (Bilby et al. 1998; Wipfli et al. 1998; Kiffney and Richardson 2001; Naiman et al. 2002; Minakawa et al. 2002; Gende et al. 2002; Wipfli et al. 2003; Lang et al. 2006; Pearsons et al. in press).

The majority of past research on woody debris and MDN has been accomplished in artificial or natural stream channels with previously established aquatic communities. However, the effect of woody debris or MDN addition on stream foodwebs in newly-created fish habitat is unknown. We have a unique opportunity here to examine how the aquatic community, over multiple trophic levels, is affected by these restoration activities in newly-formed, off-channel fish habitat. For this study, formal analyses of limiting factors were not conducted, but experimental restoration treatments were applied to address potential habitat limitations by in-stream cover and food. The objectives of this study were to 1) measure how aquatic communities (biofilm, invertebrates and fish) respond to additions of woody debris bundles and MDN, and 2) determine if aquatic community colonization and development could be accelerated through these additions. These objectives were accomplished by comparing dissolved nutrients; chlorophyll-*a* standing stock; benthic invertebrate mass, density and community structure; and fish density, standing stock, body condition and diet among selected treatments of woody debris bundle and salmon analog additions to newly-created, off-channel stream habitats. We predicted aquatic communities in habitats receiving woody debris or MDN would show signs of increased growth and carrying capacity (e.g., more biofilm biomass, more and bigger invertebrates and fish), whereas habitats without additions would show signs of density-dependent limitation (e.g., less biofilm, less and smaller invertebrates and fish). Additionally, we expected habitats receiving the combination of woody debris bundles and MDN would support the greatest abundance and mass of biofilm, invertebrates and fish. We further speculated that fish within these habitats would have the highest body condition, by directly benefiting from the increased shelter and prey.

Methods

Study sites

This study was conducted on Resurrection Creek, which drains a 414 km^2 watershed on the Kenai Peninsula, Alaska (60°53'9"N, 149°38'1"W; Figure 1). In 2005, managers from the USDA Forest Service, Chugach National Forest, began restoration of a 1.5-km reach of Resurrection Creek to mitigate the effects of a century of intensive gold mining. In the mid-1900s, this portion of Resurrection Creek was placer mined with hydraulic hoses that left the stream reach with minimal channel sinuosity and pool habitat, little in-stream woody debris or boulders, and almost no connection to the floodplain or off-channel habitats. Blanchet and Wenger (1993) speculated these alterations led to a considerable decline in available spawning and rearing habitat for the five species of Pacific salmon that return to Resurrection Creek each year. Off-channel rearing habitats and similar pool types found along side-channels and the floodplain of undisturbed stream reaches are critical rearing habitats for juvenile salmon (Bugert and Bjornn 1991; Bugert et al. 1991; Nickelson et al. 1992b; Bell et al. 2001). In light of this information and the Forest Service's pre-existing plan to restore the mining-impacted stream reach, restoration crews increased the amount of off-channel rearing habitat (alcoves) throughout the floodplain. Alcoves are backwater areas typically created by scouring of weaker substrate near meander bends or backwater areas left by uprooted trees in a less-impacted system. These habitats are common in reaches of Resurrection Creek not directly affected by past mining activities. Forest Service fisheries biologists speculated that more off-channel habitats would increase the capacity of the restored stream reach to support juvenile salmon, and in theory, although not tested here, lead to greater returns of adult salmon (Solazzi et al. 2000).

Study design

We conducted this study over the 2006 season. Working with heavy equipment operators (restoration contractors), we located suitable areas along the newly formed channels and then excavated 12 alcoves with a 0.76 m^3 backhoe. Physical characteristics of the alcoves were based on measurements taken from natural off-channel habitats in a reference reach of Resurrection Creek during 2005 (Appendix A). Sites were connected to the flowing channel on one side where surface water exchange took place (Appendix B). Restoration contractors constructed and opened the alcoves to the channel within one week of each other to minimize variation in aquatic community colonization between alcoves. Dissolved nutrient samples were collected four times (30 June, 17 July, 7 August, and 28 August) over the study from the middle of the alcove at mid-depth. We filtered (Whatman® GF/F, 0.45 μm pore diameter) two samples into 30 mL Sarstedt® bottles for NO_3^-, NH_4^+, and orthophosphate analysis. Total nitrogen (TN) and phosphorous (TP) samples were collected in a 125 mL Nalgene® and received one drop of 1:1 sulfuric acid (LaMOTTE Company, Chestertown, Maryland) before being placed on ice. Cook Inlet Keeper (Homer, Alaska) analyzed the samples according to the methods of Armstrong et al. (1967) for NO_3^-, Slawyk and MacIsaac (1972) for NH_4^+, Bernhardt and Wilhelms (1967) for orthophosphate, and an alkaline persulfate digestion procedure for TN and TP. Conductivity and dissolved oxygen was measured (YSI 85, YSI, Inc., Yellow Springs, Ohio) prior to sampling foodweb responses from 30 June – 4 September, 2006 (Appendix C). Temperature information was recorded at the center of each alcove every two hours from June to September using Onset HOBO® Pendant data loggers. These data were used to estimate mean daily and summer maximum temperature for each site and treatment (Appendix D). We sampled biofilm standing stock (via chlorophyll-*a* analysis) three times (17 July, 7 August, and 28 August), and juvenile coho, *Oncorhynchus kisutch,* density, standing stock and body condition four times over the season (30 June, 17 July, 7 August, and 28 August). Benthic invertebrates and coho diet were also sampled at the end of the study.

Experimental treatments

During the summer of 2005, we conducted pilot research on the effectiveness of adding MDN via macerated pink salmon carcasses to boost aquatic community development in newly created alcoves. Carcass enrichment led to elevated chlorophyll-*a* standing stock, benthic invertebrate density and mass, and coho body condition (A. Martin, unpublished data). However, similar to other carcass enrichment studies, acquisition and processing of carcasses was time intensive (A. Martin personal observation; Pearsons et al. 2007). Salmon carcass analogs provided the source of MDN for this study to address these limitations.

Individual alcoves were the experimental unit to which treatments were applied. The four treatments were: 1) control, 2) woody debris bundle addition, 3) salmon analog addition, and 4) woody debris bundle plus salmon analog addition (here after referred to as control, wood, analog, and analog+wood). Logistics of constructing alcove habitats limited replication to three. A randomized complete block design was used to assign treatments evenly across the study area. Alcoves were blocked according to substrate type (cobble or silt) and wood presence (i.e. logs, root wads) due to anecdotal evidence from 2005 pilot research, suggesting that these environmental factors may influence responses. The control treatment received no wood or analog additions. The wood treatment received woody debris bundles at 1 bundle/15 m^2. This density was similar to densities of woody debris found in reference alcoves of Resurrection Creek and past research (Giannico 2000). Woody debris bundles were placed on 19 July and consisted of 20, 1-m long sections of spruce, alder or cottonwood (~diameter 20-mm) tied together and anchored to the bottom of the alcove (Giannico 2000; Giannico and Hinch 2003). The carcass analog pellets used in the analog treatment were manufactured from compressed salmon carcasses and marine fish bone meal and are designed to release MDN slowly over time, imitating carcass decomposition (Bio-Oregon, Inc., Warrenton, Oregon). Several advantages of using carcass analogs exist, including: they are 1) pathogen free, 2) easy to store and distribute, 3) available year round, and 4) produce similar effects on aquatic foodwebs as real carcasses (Wipfli et al. 2004; Pearsons et al. 2007; Pearsons et al. in press). We added the 3 x 1.5 mm pellets at a rate of 1.68 kg/m^2 over three weeks (19 July to 1 August) to resemble salmon run timing and carcass deposition. After one week, analogs fragmented into small pieces and had formed a thick, organic layer mixed with silt on the substrate after two weeks. Our analog+wood treatment received both wood bundles and the analogs at the rates described above.

Biofilm

We measured chlorophyll-*a* (chl.-*a*) from biofilm by determining standing stock (ug/cm^2) on 5 x 5 cm (area = 10.16 cm^2) unglazed, ceramic tiles that were placed randomly throughout the alcoves one week after site creation (Wipfli et al. 1998, Cardinale et al. 2002). To account for possible variation within the site, we randomly selected tiles from each third of the site. As tiles were removed from the water some sloughing of biofilm was observed. Although minimal amounts were lost, the results may actually underestimate the true amount of biofilm in all treatments. Further, a fine silt layer accumulated on the tiles over the season, possibly inhibiting biofilm growth in all treatments. After tiles were removed, we scraped and brushed the biofilm from the surface into a 250 mL Nalgene® bottle to comprise the sample for each site. The samples were then wrapped with aluminum foil and then frozen until analysis. In the lab, samples were thawed and poured onto 4.7 cm glass microfibre filters (Whatman® GF/F) and chl.-*a* was extracted in 10 mL of 90% acetone for ~24 hours in a dark refrigerator. A spectrophotometer (Beckman DU® 640B) was used to measure absorption from the extracted material, from which chl.-*a* standing stocks were calculated (Jeffrey and Humphrey 1975).

Benthic invertebrates

We collected aquatic invertebrates that had colonized each alcove with 13 x 18 x 4 cm (volume = 936 cm^3) Vexar® benthic substrate baskets that had been placed randomly in each third of the alcoves one week after the alcoves were constructed. At the end of our study, crews randomly selected three baskets from the alcove as sub-samples and combined them as a composite sample (Wipfli et al. 2004). Invertebrates were washed from the debris through a 250 μm sieve and preserved in 70% ethanol. Excessively large samples dictated subsampling. A Caton Tray or Folsom Plankton Splitter was used to subsample until a minimum of 300 individuals was reached (Caton 1991). All invertebrates were sorted from the debris and identified to Order or Family level using Merritt and Cummins' (1996) or McCafferty's (1998) freshwater invertebrate keys. Aquatic adult and terrestrial invertebrates were grouped together and excluded from analyses. The number of invertebrates was divided by the area of the baskets to estimate invertebrate densities (number/cm^2). Samples were dried at 55°C for 24 hr to estimate invertebrate dry mass (mg/cm^2).

Juvenile coho salmon

We used multi-pass electrofishing to collect juvenile coho to estimate density, standing stock, body condition and diet (prey abundance and mass). The study alcoves had one opening to the channel, which was blocked with a net (4.8-mm mesh seine) during each sampling occasion. Thus, fish movement in and out of alcoves was prevented, meeting a key assumption of the removal techniques used (Zippen 1958; White et al. 1982). After placing the block net, a three-person crew conducted three passes with a backpack electrofishing unit (SmithRoot LR-24®, SmithRoot Inc., Vancouver, WA). Similar electrofishing settings of medium voltage (300-380 V), low pulse frequency (40-60 Hz) and a constant duty cycle of 25% were used throughout the study. Collected fish were placed in a bucket of stream water, anesthetized (clove oil), weighed (nearest 0.01 g), and measured (total length, nearest 1.0 mm). In addition, stomachs were pumped from a random sub-sample of six live, juvenile coho to determine prey mass, abundance and composition. Meehan and Miller (1978) demonstrated that this non-lethal technique can be 96% effective in evacuating stomach contents of juvenile coho. Only fish >40 mm were used for diet samples because we believed flushing stomachs of fish smaller was injuring them and gape limitation could influence prey selection for smaller individuals. Stomach contents were rinsed into a Whirl-Pak® bag and preserved in 70% ethanol for future analysis. Fish were placed into an aerated bucket until all had appeared to recover and then were released back into the alcove.

We used the computer software program CAPTURE to estimate coho abundance with the removal model (Rexstad and Burnham 1991). Removal model assumptions are (1) a closed population and (2) equal capture probability for all individuals and all sampling occasions (e.g., passes). However, heterogeneity in capture efficiency over removal passes (i.e., a decrease in capture probability from pass to pass) can result in underestimates in fish abundance (Zippen 1958; Peterson et al. 2004; Rosenberger and Dunham 2005). We attempted to account for differences in capture probability due to fish behavior and heterogeneity by using Otis et al. (1978) goodness-of-fit tests; however these tests are not always reliable for detecting heterogeneity (Rosenberger and Dunham

2005). Furthermore, Rosenberger and Dunham (2005) concluded the variability in bias of removal estimates can be related to several site-scale habitat conditions. Because we conducted sampling in small, confined habitats with similar characteristics, bias is most likely consistent from sample to sample; therefore the study presents fish densities as a relative measure of fish abundance in the alcoves. We estimated coho density (number/m^2) by dividing the estimated population abundance of fish by the area of each site. Estimated standing stock (g/m^2) was calculated by summing the mass of all the fish in each site and dividing that value by the area of each site. We estimated fish body condition (K_L) using Fulton's equation $K = (W/L^3) * 100{,}000$ (Anderson and Neumann 1996). Invertebrates from coho diet samples were identified and analyzed in the same manner as the benthic samples.

Data analysis

All analyses were performed with SAS version 9.1 (SAS Institute 1989). We used a two-factor repeated measures analysis of variance (ANOVAR) to test for treatment differences in dissolved nutrient concentrations, chl.-*a* standing stock, and juvenile coho density, standing stock and body condition. For these analyses, fixed factors included before and after (BA) treatment application, analog, wood, as well as the interactions of analog*BA, wood*BA, analog*wood and analog*wood*BA at $\alpha = 0.05$. We also used ANOVAR to examine the overall change between response variable levels before treatment application and after treatment application. To do so, we estimated the least-square-mean (LSM) differences, (LSM from after manipulation data – LSM from before manipulation data) for each response variable except the dissolved nutrient data.

A two-factor ANOVA was used to test for treatment differences in benthic invertebrate and diet sample responses. Our fixed effects were analog, wood and the analog*wood interaction ($\alpha = 0.05$). We found no relationship between response variables and maximum summer water temperature using multiple regression. We therefore excluded it as a covariate for all statistical analyses.

Planned contrasts for all responses were: (1) control versus wood, (2) control versus analog, (3) control versus analog+wood, (4) wood versus analog, (5) wood versus analog+wood, and (6) analog versus analog+wood. Contrasts 1 and 2 tested for the effect of the addition of wood or salmon analogs, contrast 3 tested for an effect from the analog and wood combination, and contrasts 4-6 examined the differences between adding wood, analog or analog+wood compared to the other. The six planned contrasts were tested for the sampling periods following treatment application (7 August and 28 August) by use of least-significant-difference (LSD) mean comparison test with an adjusted α = 0.0083 (0.05/6) for each contrast. Prior to statistical analyses, data for all response measures were tested against the ANOVA assumptions of normality, equal variance, and independence. Data that violated the assumptions were transformed with standard transformations (i.e., $\sqrt{x}$ and log(x)).

Regression analyses were used to examine how coho density affected average coho body mass for each treatment. We used t-tests to test for significant differences between slopes of the regression line for each treatment ($\alpha = 0.05$). The standard errors for the differences between each pair of slopes were calculated and used with the slope estimates to derive t-statistics. We additionally examined the similarity between the proportion of benthic invertebrate categories in the coho diet samples to the proportion of benthic invertebrate categories collected from the benthic substrate baskets to determine if juvenile coho fed on the expected increase in invertebrate densities (due to treatment additions). This was done using Morisita's overlap index as modified by Horn in Krebs (1999):

$$C_H = \frac{2\sum X_{ij} X_{ik}}{[(\sum X^2_{ij} / N^2_j) + (\sum X^2_{ik} / N^2 k)] N_j N_k}$$

The similarity coefficient C_H can range from 0 to 1. $C_H = 0$ when there is no overlap, and 1 when the proportions are identical. X_{ij} and X_{ik} are the number of individuals of species *i* in sample *j* and sample *k*. N_j and N_k equal the total number of individuals in each sample, *j* and *k*. Our level of significance was set at $C_H > 0.60$, as described by Zaret and Rand (1971). Values for C_H greater than 0.60 suggest that the same invertebrate categories were commonly found in the artificial substrate baskets and coho diet.

Results

Site characteristics

Mean alcove surface area ranged from 49 to 63 m^2 and mean maximum water depth ranged from 0.8 to 1.0 m across the four treatments (Table 1). Mean daily water temperature ranged from 7.1 to 8.2 °C and maximum water temperature ranged from 9.4 to 11.8°C throughout the study. Mean conductivity ranged from 62.8 to 69.2 uS/cm^1 and average dissolved oxygen saturation ranged from 95 to 108%. As expected, the concentrations of all the measured dissolved nutrients tended to increase in the treatments that received analogs (ANOVAR: analog; $F_{TP} = 20.3$, $P_{TP} < 0.001$, $F_{Orthophosphate} = 20.0$, $P_{Orthophosphate} < 0.001$, $F_{TN} = 10.8$, $P_{TN} = 0.003$, $F_{NH4} = 20.5$, $P_{NH4} < 0.001$; Figure 2, Appendix E), with the exception of NO_3^- (ANOVAR: analog; $F_{NO3} = 0.01$, $P_{NO3} = 0.934$). Seven days after treatments were applied (7 August), mean dissolved nutrient concentrations in the analog treatment were on average 140 times higher than the control treatment (LSD contrast: $P_{TP} < 0.01$, $P_{Orthophosphate} < 0.001$, $P_{TN} = 0.008$, $P_{NH4} < 0.001$) and 67 fold higher than wood treatment (LSD contrast: $P_{TP} < 0.01$, $P_{Orthophosphate} = 0.007$, $P_{TN} = 0.004$, $P_{NH4} < 0.001$), excluding NO_3^- data. The overall concentrations also increased in analog+wood treatment, but not to the extent of the analog treatment. On 7 August, overall nutrient concentrations in the analog+wood treatments were on average 74 times higher than the control (LSD contrast: $P_{TP} < 0.01$, $P_{PO43-} < 0.001$, $P_{TN} = 0.012$, $P_{NH4} < 0.001$) and 30 times higher than wood treatment (LSD contrast: $P_{TP} = 0.02$, $P_{Orthophosphate} = 0.002$, $P_{TN} = 0.006$, $P_{NH4} < 0.001$). NO_3^- remained at base concentrations after treatments were applied (ANOVAR: BA: $F_{NO3-} = 0.11$, $P_{NO3-} = 0.743$) and began to rise on 28 August (40 days after initial enrichment), with the largest increases in the analog and analog+wood treatments.

Biofilm

Chl.-*a* standing stock was substantially higher in all alcoves that received salmon analogs after treatments were applied (ANOVAR: analog; $F = 10.6$, $P = 0.003$, analog*BA; $F = 8.01$, $P = 0.009$; Figure 3a, Table 5, Appendix F). The greatest change in chl.-*a* after treatments were applied was in the analog treatment, nearly 8 times more than the control treatment (Figure 3b). Standing stock in the analog treatment was 4-10 times higher than levels in the control and wood treatments on 7 August (LSD contrast: $t = -2.49$, $P > 0.0083$, $t = -3.70$, $P = 0.001$; Figure 4a) and 2-3 times higher by 28 August (LSD contrast: $t = -1.72.$, $P > 0.0083$, $t = -1.13$, $P > 0.0083$). Chl.-*a* was also higher in the analog+wood treatment than at the control and wood treatments on 7 August (LSD contrast: $t = -1.53$, $P > 0.0083$, $t = -2.75$, $P > 0.0083$) and 28 August (LSD contrast: $t = -2.22$, $P > 0.0083$, $t = -1.62$, $P > 0.0083$).

Benthic invertebrates

We detected no significant effects of wood or analog addition on benthic invertebrate density or mass (ANOVA: density; $F_{\text{analog}} = 0.001$, $P_{\text{analog}} > 0.05$ & $F_{\text{wood}} = 0.12$, $P_{\text{wood}} > 0.05$, mass; $F_{\text{analog}} = 0.46$, $P_{\text{analog}} > 0.05$ & $F_{\text{wood}} = 0.06$, $P_{\text{wood}} > 0.05$; Figure 4a and b, Table 5, Appendix F). Benthic invertebrate communities were dominated by Diptera larvae in all four treatments ($\bar{X}_{\text{abundance}} = 82\%$, $\bar{X}_{\text{mass}} = 70\%$). Chironomidae (Diptera: Chironomidae) contributed to the majority of the Dipteran families, comprising 74 to 98% of the total number of invertebrates and 63 to 84% of the total mass (highest in analog+wood; Table 2). The Other Aquatic category (i.e., hydracarinids, copepods, ostracods, turbellarids and oligochaetes) comprised 14% of invertebrates in the treatments, and was highest in the control treatment ($\bar{X} = 22\%$). The Ephemeroptera, Plecoptera, Trichoptera and Coleoptera category was the next most abundant ($\bar{X} = 2\%$) for all treatments. In general, limnephilid caddisflies and heptageniid mayflies contributed most to this category ($\bar{X} = 2\%$ and $\bar{X} < 1\%$).

Juvenile coho salmon

Density – We captured and measured nearly 2,700 juvenile coho over the summer of 2006. Juvenile coho density was highly variable across alcoves, but estimated fish density increased in most alcoves throughout the summer (Figure 5a). The control treatment had the highest number of fish before treatments were applied, then density declined for the next two sampling occasions, while densities increased in the other three treatments. No fish were captured in the analog+wood alcoves on 30 May, but there was a steady increase in coho density in the subsequent sample sessions for this treatment. Overall, mean coho densities were considerably lower in analog and analog+wood treatments throughout the study (ANOVAR: $F = 42.01$, $P < 0.001$, Appendix G). The wood treatment had the highest mean density going into fall ($\bar{X}_{7\text{August}} = 2.3$, $\bar{X}_{28\text{ August}} = 2.5$ coho/m^2) compared to the other treatments at that time period, yet no significant wood effect was detected during the study (ANOVAR: $F = 2.12$, $P > 0.05$). The overall change in fish density after treatments were applied was similar for the four treatments (Figure 5d, Table 5). We found no treatment differences from the contrasts of controls versus any other treatment across the study. On 7 August and 28 August (after the treatment additions), mean density in the wood treatment was 2.5 times and 5 times higher than analog treatment (LSD contrast: $t_{7\text{Aug.}} = 1.60$, $P_{7\text{Aug.}} > 0.0083$, $t_{28\text{Aug.}} = 2.17$, $P_{28\text{Aug.}} > 0.0083$) and 7 times and 5.5 times higher than the analog+wood treatment (LSD contrast: $t_{7\text{Aug.}} = 2.80$, $P_{7\text{Aug.}} = 0.007$, $t_{28\text{Aug.}} = 2.80$, $P_{28\text{Aug.}} > 0.0083$). Fish density was inversely related to mean individual coho mass in the control treatment (Figure 6). Furthermore, the slope of the relationship between coho density and mean coho mass for control treatment was significantly different than the slope of the other three treatments (control vs. wood: $t = -2.83$, $P < 0.05$; control vs. analog: $t = -2.13$; $P < 0.05$; control vs. analog+wood: $t = -2.04$, $P < 0.05$).

Standing stock – Our estimates of coho standing stock follow similar patterns as density, however, standing stock continued to increase in all alcoves after treatments were applied (ANOVAR: BA; $F = 15.4$, $P < 0.001$; Figure 5b). Alcoves that received the analog (ANOVAR: $F = 27.3$, $P < 0.001$) and the analog+wood (ANOVAR: $F = 4.17$, $P = 0.049$) treatments consistently had lower mean fish biomass than the wood treatment ($\bar{X}_{\text{summer}} = 2.1$ g/m^2), yet no significant wood effect was detected across the summer (ANOVAR: $F = 2.44$, $P > 0.05$). No differences for the overall change in treatments or our planned contrasts between treatments were detected for standing stock (Figure 5e, Table 5).

Body condition – In general, the body condition of juvenile coho increased in all alcoves throughout the study (ANOVAR: $F = 324.4$, $P < 0.001$; Figure 5c, Table 5). As expected, there was a strong affect of analogs on body condition (ANOVAR: $F = 71.6$, $P < 0.001$). Fish condition was >2 times higher for fish in the analog enriched treatments than fish in control and wood treatments (ANOVAR: analog*BA; $F = 6.4$, $P = 0.012$). Body condition responded most dramatically for fish inhabiting alcoves that received the analog+wood addition (ANOVAR: $F = 9.74$, $P = 0.002$), with the additive effect of analog+wood resulting in the highest mean body condition ($\bar{X} = 1.15$) and overall change (Figure 5f) on 28 August. At that time, body condition in the analog treatment was also higher ($\bar{X} = 1.04$) than the control and wood treatments. Based on planned contrasts for 7

August, condition of fish in the control treatment was slightly higher than fish in the wood treatment (LSD contrast: $t = 3.36$, $P < 0.001$), while the control treatment was considerably lower than analog+wood (LSD contrast: $t = -3.59$, $P < 0.001$). No differences were detected between the control and analog treatments (LSD contrast: $t = -0.20$, $P > 0.05$). Mean fish condition was higher in analog (planned contrast: $t = -2.77$, $P = 0.006$) and analog+wood (LSD contrast: $t = -5.63$, $P < 0.001$) treatments compared to fish in the wood-treated alcoves shortly after treatments were added. Analog and analog+wood treatments (LSD contrast: $t = -3.08$, $P = 0.002$) were also significantly different on 7 August. At the end of our study, body condition was almost equal between control and wood treatments and changed minimally since treatments were applied (LSD contrast: $t = 0.22$, $P > 0.0083$). Inversely, analog and analog+wood sites continued to increase. Coho body condition in the control treatment was markedly lower than in analog (LSD contrast: $t = -3.53$, $P < 0.001$) and analog+wood (LSD contrast: $t = -7.13$, $P < 0.001$) treatments. Condition was also much lower in the wood treatment compared to the analog and analog+wood treatments (LSD contrast: $t = -3.49$, $P_{analog} = 0.006$, $t = -7.86$, $P_{analog+wood} < 0.001$). Furthermore, mean fish body condition in analog+wood ($\bar{X} = 1.15$) was higher (LSD contrast: $t = -2.87$, $P = 0.015$) than fish condition in analog treatment ($\bar{X} = 1.04$) at the end of August.

Diet – Mean abundance and mass of benthic invertebrates in the diet of juvenile coho was highest in the analog and the analog+wood treatments, with a significant analog effect (ANOVA: abundance; $F_{analog} = 14.1$, $P_{analog} = 0.0004$, biomass; $F_{analog} = 15.85$, $P_{analog} = 0.0002$; Figure 4c and d, Table 5). Invertebrate abundance from diet samples of fish in the analog treatment ($\bar{X}$ = 25.3 prey items/fish) were nearly 2 times higher than the control (LSD contrast: $t = 2.95$, $P = 0.005$) and the wood treatments (LSD contrast: $t = -2.62$, $P > 0.0083$). Invertebrate abundance was also higher (2 times) in analog+wood manipulation compared to our control (LSD contrast: $t = 2.69$, $P > 0.0083$) and wood treatments (LSD contrast: $t = 2.39$, $P > 0.0083$; Figure 5c). The only significant differences in mass were in the control versus analog (LSD contrast: $t = 3.68$, $P < 0.001$) and control versus analog+wood (planned contrast: $t = 4.12$, $P < 0.001$; Figure 5d) contrasts, with prey mass in analog and analog+wood treatments being 3 times heavier than prey in the control treatment.

Percent composition of invertebrates in coho diets followed very similar patterns to the proportions in the benthic invertebrate community. Diptera made up the majority of prey in all coho diets across treatments. Chironomidae was the most abundant Family and contributed the most to total insect biomass ($\bar{X}_{abundance}$ = 63%, $\bar{X}_{mass}$ = 43%; Table 3). The Adult/Terrestrial group, mostly Dipterans and Coleopterans, contributed the next largest amount across treatments ($\bar{X}_{abundance}$ = 14%, $\bar{X}_{mass}$ = 20%). The Ephemeroptera, Plecoptera, Trichoptera and Coleoptera category contributed the third largest amount across all four treatments, made up mostly of heptageniid and baetid mayflies, and nemourid stonefly larvae. Composition of invertebrates in the diets of the juvenile coho did significantly overlap (C_H > 0.60) with the composition of the benthic invertebrates from the artificial substrate baskets for all treatment types (Table 4).

Discussion

In the months following alcove creation and treatment application in Resurrection Creek, we observed higher accumulations of biofilm, greater abundance and size of invertebrates in coho diets, and higher body condition of juvenile coho salmon in the alcoves to which salmon analogs were added. We speculate the invertebrates and juvenile coho benefited from the analog additions through two possible trophic pathways: direct benefit from feeding on the analog fragments and indirect benefit through bottom-up effects from the increased nutrients assimilated by the biofilm subsequently transferred through trophic levels (Wipfli et al. 1998). We detected significant increases in chl.-*a* standing stock in analog enriched treatments similar to the findings of Wipfli et al. (1998) in southeastern Alaska. This increase in biofilm standing stock may have attributed to elevated benthic invertebrate densities and mass in the analog and analog+wood treatments, as many of the collected invertebrates were algivores (Deegan et al. 1997; Wipfli et al. 1998). Although we detected no significant treatment differences in our benthic invertebrate estimates, these estimates may be underestimating true densities and biomass because invertebrates were not excluded from fish predation. Furthermore, it appears coho fry were strongly relying on benthic food resources in the alcoves, as suggested by the high similarity between benthic invertebrate and diet invertebrate composition. With greater invertebrate densities and mass within analog and analog+wood treated alcoves, quantity (and possibly quality) of available prey items likely increased. Chironomid midges comprised the greatest proportion of invertebrates (density and mass) in the substrate baskets and coho diets for all four treatments, although chironomid density and mass was highest in the two analog-enriched treatments. Similarly, Wipfli et al. (1998) found midges accounted for nearly 85% of total macroinvertebrate abundance in salmon carcass enriched channels. Several other studies in Alaska have illustrated the importance of midge larvae as prey items for stream-rearing, juvenile salmonids (Loftus and Lenon 1977; Wipfli 1997; Chaloner and Wipfli 2002; Hicks et al. 2005). Furthermore, Angermeier and Karr (1984) found the presence of woody debris significantly increased aquatic invertebrate and fish abundance, speculating that the wood provided cover (i.e., predation and current refugia) and food resources (i.e., bacteria, fungi, invertebrates). Considering this, and the effects of the analogs, we speculate the analog+wood treatment increased the capacity of the habitat the most for the developing aquatic community. Because of the increased cover and food (i.e., more biofilm, invertebrates), fish in these sites could be expected to survive and perform better than fish in off-channel habitats with limited resources (Wipfli et al. 2004).

We detected coho inhabiting the newly formed alcoves as soon as two days after construction, and density generally increased over the duration of the study. These results support past research investigating the importance of off-channel habitats for juvenile coho. Juvenile coho have a strong preference for these types of off-channel habitats going into fall and winter (Nickelson et al. 1992a) and a much higher fidelity (50%) to them than to main-channel pools (7%), apparently for flow refugia (Bell et al. 2001). Overall, coho density and standing stock increased similarly in the wood, analog and analog+wood treatments after treatments were applied. However, density was highest in the wood treatment throughout the latter part of the study. Similar to our findings, coho salmon and steelhead trout *O. mykiss* density and survival increased in Washington and Oregon streams that received varying types of wood addition (Cederholm et al. 1997; Johnson et al. 2005). Winter carrying capacity of restored side-channels increased for juvenile coho as a result of wood supplementation (Giannico et al. 2003). Furthermore, rainbow trout *O. mykiss* density and biomass increased in several small, Colorado mountain streams after woody debris was added; however, these changes were attributed to immigration and not increases in survival, recruitment, or fish growth (Gowan and Fausch 1996). Several possible explanations could account for these results, such as increased invertebrate production (Angermeier and Karr 1984), increased physical refugia from predation (Reinhardt and Healey 1997), or increased visual isolation from intraspecific competitors (Dolloff 1986). Although density and standing stock were higher in the wood treatment, fish condition was lower than fish in analog enriched alcoves going into the fall. Woody debris forms complex habitat that can isolate fish from each other, thus allowing more to occupy an area (Dolloff 1986). Because of the higher density of fish in the wood treatment, it is plausible that food was more limiting than in analog enriched alcoves, resulting in the lower coho body condition in late summer. To determine if this is occurring, we propose future studies could examine the energetic costs of fish in similar conditions and habitats.

After treatments were applied, coho density dropped abruptly in the control treatment, yet standing stock continued to increase. In contrast, the other three treatments showed increases in density and standing stock going into fall. Additionally, we found that fish density was inversely related to fish body mass in the control treatment. We speculate this may be a result of resource limitation and population self-thinning (Keeley 2003). Self-thinning theory predicts that as fish mass increases in an area, the number of fish competing for limited resources must decline due to density-dependent factors (Keeley 2003). For example, resources appeared to become limiting and fish densities decreased as brown trout *Salmo trutta* grew in a river of northwestern Spain (Rincon and Lobon-Cervia 2002). Likewise, density-dependent responses (i.e., mortality and emigration) increased as juvenile steelhead density increased and as food abundance decreased (Keeley 2001). From these findings, we speculate that as coho fry in the control treatment grew bigger, they became limited in available resources (i.e., shelter, food, territory size) and intraspecific competition forced some individuals to emigrate from the alcoves.

Density and standing stock of juvenile coho varied among alcoves at the beginning of our study. For example, the control alcoves and alcoves treated with wood had higher density and standing stock than the other treatments. We believe this initial variability was an artifact of site location, where coho density in the most recently created stream channels was lower than channels that had been established early in the restoration process. We assume that, once the coho fry emerged from the gravel, they began searching out suitable rearing habitat and colonized the most accessible alcoves. The three alcoves that were assigned the analog+wood treatment were on side channels of Resurrection Creek. Two of those alcoves were in the upper stretch of the restoration project in a region that was rerouted through a network of channels later than the channels surrounding other alcoves. As a result, we hypothesize that the low density recorded for this treatment was partly due to a lag effect in fish moving into the new channel and then colonizing the alcoves.

When transferring these results, several factors should be considered that could possibly influence future restoration success using these techniques in coastal systems similar to Resurrection Creek. For example, water temperature has been recognized to influence biofilm growth, invertebrate life histories and fish productivity (Hogg and Williams 1996; McCullough 1999). Minimal differences in water temperatures were detected during our study. However, it is expected that a system with warmer temperatures would experience greater changes in response variables. The presence of riparian vegetation could also possibly influence restoration results. Allochthonous input from the terrestrial environment such as leaf litter or aquatic adult and terrestrial invertebrates can stimulate stream productivity (Minshall 1967; Wallace et al. 1997; Wipfli 1997; Kawaguchi and Nakano 2001). We speculate that allochthonous input was minimal for this study and will continue to be so until the riparian vegetation is more established. However, if these restoration techniques were used in habitats with well established riparian areas, additions of supplemental nutrients may not result in the level of changes we found. We suggest future studies consider these possible implications and that additions of salmon analogs and wood could boost the productivity of aquatic ecosystems until other trophic pathways (e.g., terrestrial input, MDN inputs from salmon runs) are reestablished.

Conclusions and management implications

This study provided a unique opportunity to test two potential restoration techniques in a system with limited resources (e.g., cover and food). Our results suggest that early-stage aquatic community development and growth in restored fish habitat can be enhanced by supplemental woody debris and nutrients via salmon analog pellets when density-dependent factors are at play. The effects of woody debris bundle additions were similar to past woody debris studies; alcoves with wood harbored higher numbers of fish and consequently had the highest standing stock. However, the wood treatment alone did not appear to influence a change in fish body condition as much as increasing food resources via nutrient enrichment. Giannico (2000) found as food resources increased in several small, suburban streams of British Columbia, juvenile coho became less reliant on pools with woody debris. From these findings, he suggested coho were willing to forgo shelter if food resources were abundant; which he considered to be risk-prone behavior. Fish body condition increased in the absence of woody debris in our analog treatment similar to Giannico's findings. However, the combination of woody debris and analogs resulted in the greatest increase in body condition. This could be due to a reduction in energetic costs of flight or foraging because of the increased quantity of cover and food resources.

Due to the responses of the aquatic community to the enrichment of MDN, our findings suggest nutrients may be limiting in these newly formed habitats. Resurrection Creek currently has one of the largest pink salmon *O. gorbuscha* runs in Turnagain Arm, Alaska, and this source of nutrients may directly and indirectly be subsidizing chinook *O.*

tshawytscha and coho salmon productivity. Furthermore, the MDN released from pink salmon carcasses may lead to higher juvenile survival, which in turn could lead to more smolt outmigrating, and possibly higher adult escapements and more nutrients for future generations of fish (Wipfli et al. 1998). With this potential positive feedback in mind, management plans might consider implementing management decisions based on a multi-species perspective if formal analyses indicate low nutrient concentrations and food production may be limiting fish productivity (Michael 1995; Wipfli et al. 2003).

Conversely, before using woody debris and salmon carcass or analog additions as a management tool for increasing juvenile coho production, possible negative effects of these treatments are important to consider. Adding too much woody debris may have potential side effects, such as increased localized fish densities and competition for food items or reduced foraging space (Gowan and Fausch 1996; Giannico 2000). Aquatic systems that are overloaded with salmon analogs or carcasses may be at risk of eutrophication or exposure to pathogens (Pearsons et al. 2007). Provided any negative consequences are avoided and other factors are not limiting salmon production (e.g., stream-wide processes), salmon carcass analog and woody debris additions appear to hold promise as viable stream restoration and fisheries management tools to increase juvenile coho production. Furthermore, future research on the effects of these additions on later life stages of coho is essential to fully understand the value of these restoration techniques (Hartman et al. 1996).

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Table 1.– Site characteristics of the 12 alcoves in Resurrection Creek, Alaska.

Site #	Treatment type	Alcove area (m^2)[a]	Maximum depth (m)	Summer mean temp. (°C)[b]	Summer maximum temp. (°C)[b]	Mean conductivity (uS/cm^1)	Mean dissolved oxygen saturation (%)
1	Wood	45.3	0.91	7.6 (0.09)	11.6	60.5 (1.4)	114.6 (0.9)
2	Analog	42.1	0.70	7.8 (0.13)	11.5	68.7 (1.7)	94.6 (3.7)
3	Control	46.0	0.95	7.5 (0.08)	8.8	72.6 (2.4)	76.6 (2.4)
4	Analog+wood	43.8	0.75	8.8 (0.15)	12.1	72.2 (4.2)	86.1 (13.3)
5	Analog	50.0	0.79	9.0 (0.13)	11.8	73.3 (3.2)	100.2 (5.7)
6	Wood	71.5	0.80	8.1 (0.12)	11.4	64.9 (2.7)	110.3 (2.7)
7	Control	59.1	1.10	7.0 (0.08)	10.9	56.6 (1.9)	120.8 (2.2)
8	Control	71.0	0.82	6.9 (0.07)	8.7	62.7 (3.5)	87.9 (4.0)
9	Analog	55.8	0.81	7.7 (0.10)	11.9	67.0 (0.5)	119.0 (1.2)
10	Analog+wood	61.1	0.76	7.7 (0.09)	10.0	72.8 (3.5)	84.3 (14.9)
11	Wood	72.4	1.00	8.0 (0.07)	9.3	63.4 (2.1)	99.2 (3.9)
12	Analog+wood	83.6	1.10	7.8 (0.10)	11.5	66.7 (0.7)	114.0 (1.7)
	Control	58.7	0.96	7.1	9.4	64.0	95.1
	Wood	63.1	0.9	7.9	10.8	62.9	108.0
Mean	Analog	49.3	0.77	8.2	11.8	69.7	104.6
	Analog+wood	62.8	0.87	8.1	11.2	70.6	94.8
	Overall	58.5	0.87	7.8	10.8	66.8	100.6

Note: Standard error (SE) is given after mean in parentheses.
[a]Alcove surface area measured by multiplying the length of the area by the average of three wetted widths.
[b]Mean and maximum water temperatures were recorded every two hr. (May-September) with Onset® HOBO temperature data loggers placed on the bottom of the alcove at the deepest location.

Table 2.– Mean composition of benthic invertebrates from artificial substrate baskets removed from alcoves four months after being placed in the newly-created alcoves.

CATEGORY	Treatment							
	CONTROL		WOOD		ANALOG		ANALOG+WOOD	
	Mean % by #	Mean % by weight	Mean % by #	Mean % by weight	Mean % by #	Mean % by weight	Mean % by #	Mean % by weight
Diptera, Chironomidae[1]	74.4%	62.9%	78.5%	65.7%	80.2%	65.5%	98.0%	83.8%
Diptera, Other[1]	0.2%	0.7%	0.4%	1.2%	2.1%	1.0%	0.0%	0.0%
Ephemeroptera[2]	0.2%	2.6%	0.6%	0.1%	0.9%	1.3%	0.1%	0.2%
Plecoptera[2]	0.4%	0.9%	0.1%	0.3%	0.0%	0.0%	0.2%	5.3%
Trichoptera[2]	3.2%	23.9%	2.3%	15.9%	0.3%	4.1%	0.4%	7.1%
Coleoptera[2]	0.0%	0.0%	0.3%	1.2%	0.0%	0.0%	0.0%	0.0%
Hydracarina[3]	0.1%	0.0%	0.4%	1.0%	0.0%	0.0%	0.0%	0.0%
Copepoda[3]	0.2%	0.6%	1.5%	4.8%	0.3%	0.7%	0.0%	0.0%
Ostracoda[3]	0.5%	0.9%	0.8%	0.9%	4.8%	1.1%	0.0%	0.0%
Turbellaria[3]	0.6%	1.5%	0.2%	0.2%	0.1%	0.9%	0.0%	0.0%
Oligochaeta[3]	20.0%	5.5%	14.7%	6.2%	10.4%	15.0%	0.6%	1.1%
Other Insecta[4]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Adult/Terristrial[5]	0.1%	0.4%	0.2%	2.5%	0.9%	10.5%	0.8%	2.6%
Total %	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 3.– Mean diet composition of juvenile coho salmon inhabiting newly-created alcoves among the four treatments.

CATEGORY	Treatment							
	CONTROL		WOOD		ANALOG		ANALOG+WOOD	
	Mean % by #	Mean % by weight	Mean % by #	Mean % by weight	Mean % by #	Mean % by weight	Mean % by #	Mean % by weight
Diptera, Chironomidae[1]	73.8%	38.7%	57.1%	34.3%	49.9%	48.7%	70.4%	48.3%
Diptera, Other[1]	0.4%	5.5%	1.7%	2.7%	0.0%	0.0%	2.4%	12.2%
Ephemeroptera[2]	3.3%	5.5%	20.2%	31.0%	4.8%	7.6%	15.6%	15.2%
Plecoptera[2]	1.7%	3.1%	3.4%	6.4%	0.9%	1.5%	1.0%	1.9%
Trichoptera[2]	0.8%	3.5%	0.0%	0.0%	0.4%	0.1%	0.3%	0.6%
Coleoptera[2]	0.4%	2.3%	0.4%	0.0%	0.2%	0.1%	0.0%	0.0%
Hydracarina[3]	0.8%	0.0%	2.1%	0.8%	1.8%	0.1%	1.0%	1.3%
Copepoda[3]	0.0%	0.0%	0.0%	0.0%	22.9%	33.0%	0.0%	0.0%
Ostracoda[3]	0.8%	0.0%	0.0%	0.0%	0.2%	0.3%	0.0%	0.0%
Turbellaria[3]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	7.8%
Oligochaeta[3]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other Insecta[4]	1.7%	1.2%	0.8%	0.0%	0.2%	2.2%	0.3%	5.9%
Adult/Terristrial[5]	16.3%	40.2%	14.3%	24.9%	18.7%	6.5%	8.5%	6.9%
Total %	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 4.– Morisita's similarity coefficients (C_H) generated from comparisons between juvenile coho diet and benthic invertebrates in the four treatments ($N = 67$ stomach samples).

	Treatment			
Sample Session	Control	Wood	Analog	Analog+wood
8/31/2006	0.96	0.92	0.88	0.95

Table 5.– ANOVA results (*P*-values) for fixed effects, interactions of fixed effects, and individual a priori contrasts of treatments to study their effect on biofilm, benthic invertebrates, and juvenile coho salmon density, standing stock, condition and diet.

Factor or contrast	TP	Ortho-phosphate	TN	NH_4^+	NO_3^-	Biofilm	Benthic density	Benthic biomass	Diet abundance	Diet biomass	Coho density	Coho standing stock	Condition
Main effects and main effect interactions (α = 0.05)													
Before and After (BA)	***<0.001***	***<0.001***	***0.0062***	***<0.001***	0.740	***<0.001***	NT[a]	NT	NT	NT	0.193	***<0.001***	***<0.001***
Analog	***<0.001***	***<0.001***	***0.003***	***<0.001***	0.934	***0.003***	0.974	0.516	***<0.001***	***<0.001***	***<0.001***	***<0.001***	***<0.001***
Wood	0.940	0.551	0.115	0.685	0.066	0.256	0.734	0.810	0.827	***0.040***	0.155	0.128	0.920
Analog*BA	***<0.001***	***<0.001***	***0.031***	***<0.001***	0.873	***0.009***	NT	NT	NT	NT	0.246	0.447	***0.012***
Wood*BA	0.904	0.787	0.743	0.805	0.624	0.486	NT	NT	NT	NT	0.162	0.531	0.781
Analog*wood	0.358	0.728	0.526	0.819	0.677	0.980	0.650	0.822	0.819	0.323	0.096	***0.049***	***<0.001***
Analog*wood*BA	0.454	0.501	0.901	0.997	0.421	0.864	NT	NT	NT	NT	0.297	0.583	***0.002***
Individual contrasts for sample session 3 (α = 0.0083)													
Control vs. wood	0.541	0.160	0.787	0.817	0.515	0.237	NT	NT	NT	NT	0.351	0.647	***<0.001***
Control vs. analog	***<0.001***	***<0.001***	***0.008***	***<0.001***	0.153	0.020	NT	NT	NT	NT	0.631	0.674	0.84
Control vs. AW[b]	***<0.001***	***<0.001***	0.012	***<0.001***	0.213	0.139	NT	NT	NT	NT	0.113	0.029	***<0.001***
Wood vs. analog	***<0.001***	***0.007***	***0.004***	***<0.001***	0.427	***0.001***	NT	NT	NT	NT	0.120	0.381	***0.006***
Wood vs. AW	***0.002***	***0.002***	***0.006***	***<0.001***	0.544	0.011	NT	NT	NT	NT	***0.007***	0.010	***<0.001***
Analog vs. AW	0.358	0.638	0.649	0.582	0.850	0.348	NT	NT	NT	NT	0.209	0.071	***0.002***
Individual contrasts for sample session 4 (α = 0.0083)													
Control vs. wood	0.665	0.927	0.907	0.969	0.221	0.559	0.935	0.743	0.740	0.026	0.300	0.478	0.83
Control vs. analog	0.028	0.018	0.135	0.014	0.194	0.098	0.765	0.537	***0.005***	***<0.001***	0.271	0.380	***<0.001***
Control vs. AW	0.065	0.066	0.644	0.054	0.816	0.036	0.792	0.530	0.009	***<0.001***	0.091	0.140	***<0.001***
Wood vs. analog	0.070	0.015	0.108	0.015	0.012	0.270	0.828	0.769	0.011	0.167	0.037	0.117	***0.006***
Wood vs. AW	0.151	0.055	0.563	0.059	0.303	0.117	0.731	0.760	0.019	0.047	0.009	0.033	***<0.001***
Analog vs. AW	0.691	0.563	0.293	0.551	0.128	0.626	0.577	0.991	0.995	0.459	0.539	0.538	***0.004***

Note: Bold italic type indicates a significant treatment difference

[a] = NT = not tested

[b] = AW = analog+wood

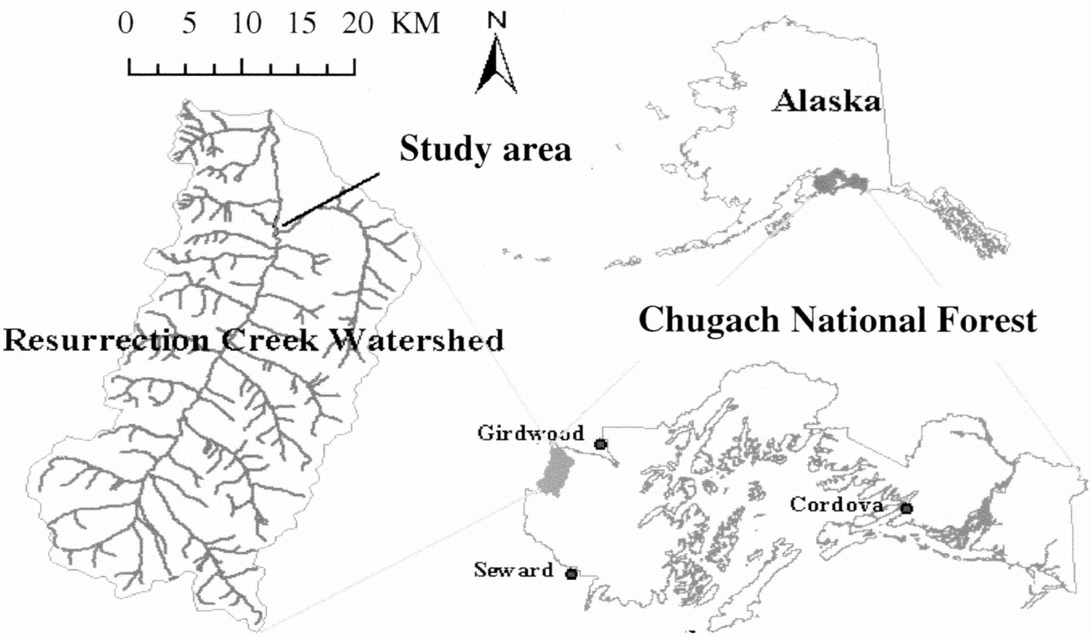


Figure 1.– Study area on Resurrection Creek, Kenai Peninsula, Alaska.

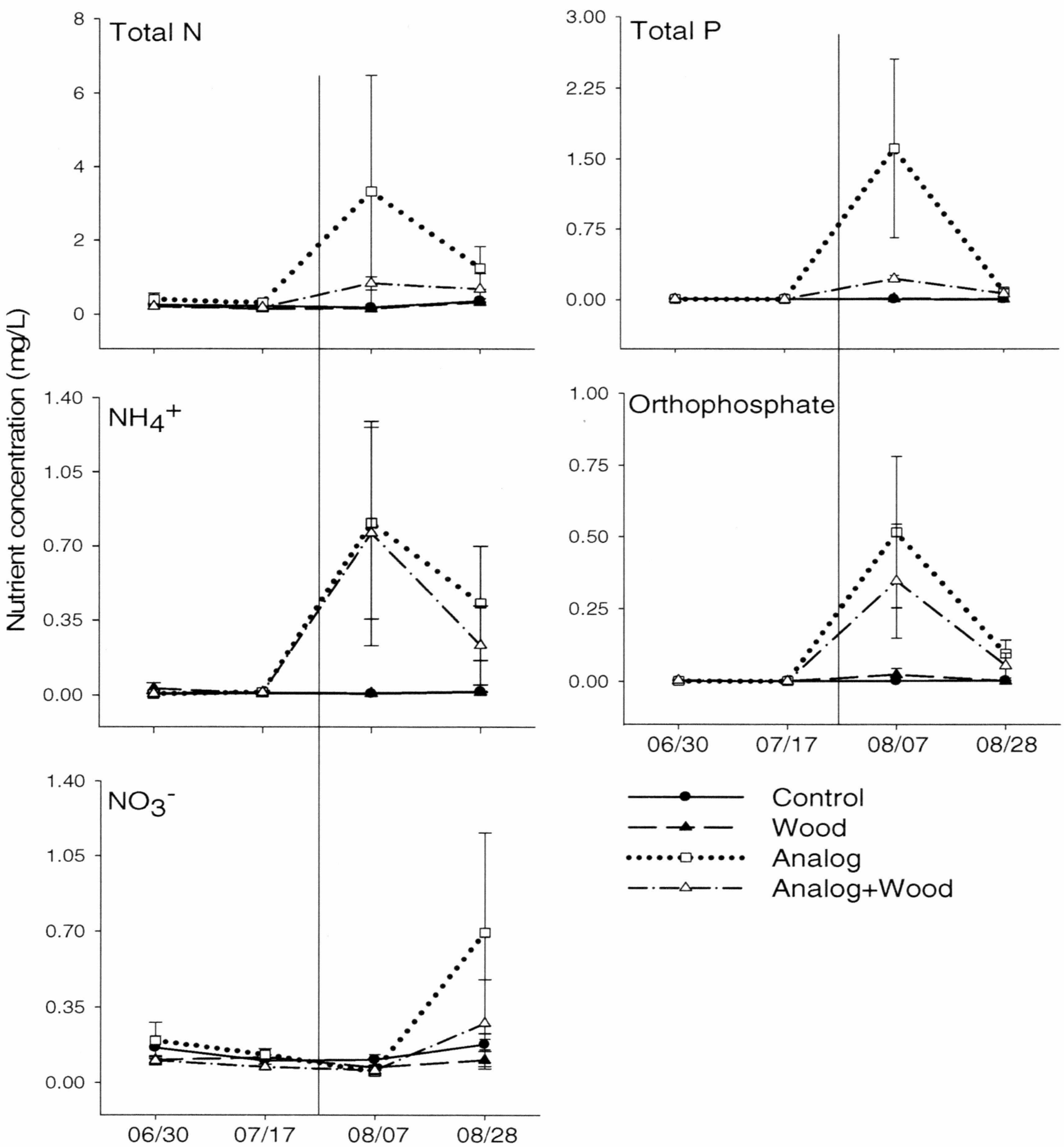


Figure 2.– Mean nutrient concentrations from June to August, 2006. Solid vertical lines in both columns represent when treatments were applied. Error bars indicate ±1 SE.

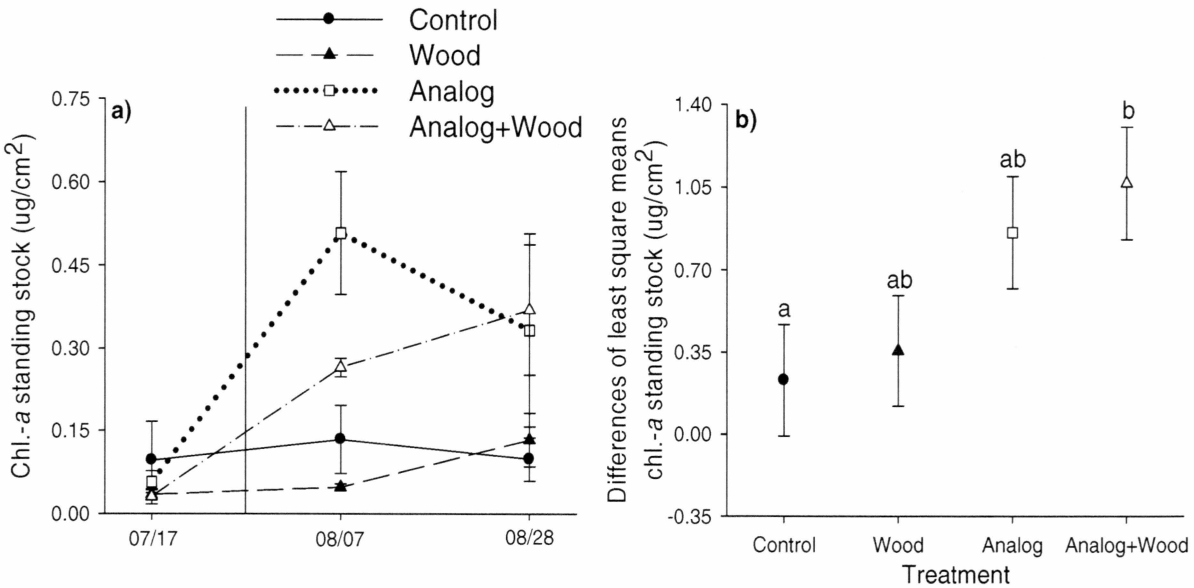


Figure 3.– Mean chlorophyll-*a* standing stock from July through August **(a)** and overall treatment differences ($\bar{X}_{after}$ - $\bar{X}_{before}$) in response to the four treatments **(b)**. Solid vertical lines represent treatment application. Error bars indicate ±1 SE. Points without similar letters are significantly different (least-significant-difference mean comparison test, $\alpha = 0.05$).

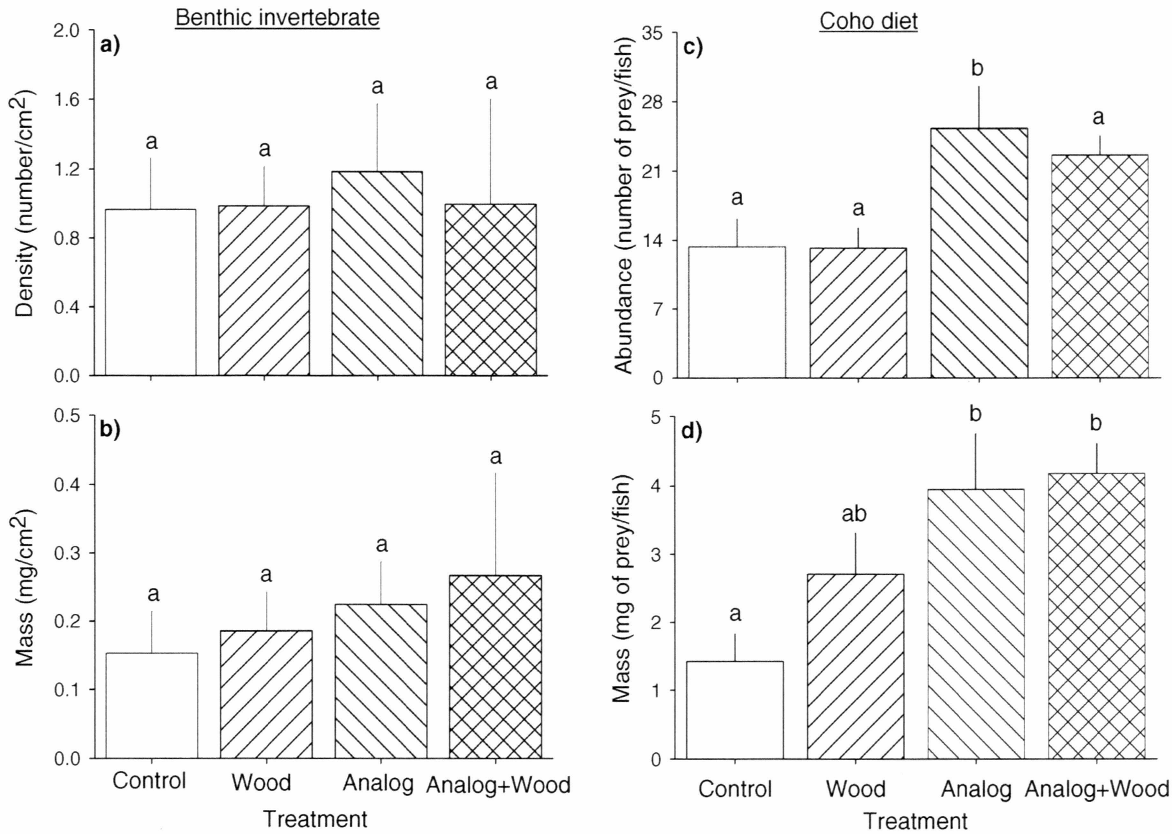


Figure 4.– Mean invertebrate density **(a)** and dry mass **(b)** of benthic substrate baskets and mean invertebrate abundance **(c)** and dry mass **(d)** of coho diets for the four treatments on 31 August, 2006. Error bars indicate +1 SE. Points without similar letters are significantly different (least-significant-difference mean comparison test, adjusted α = 0.0083).

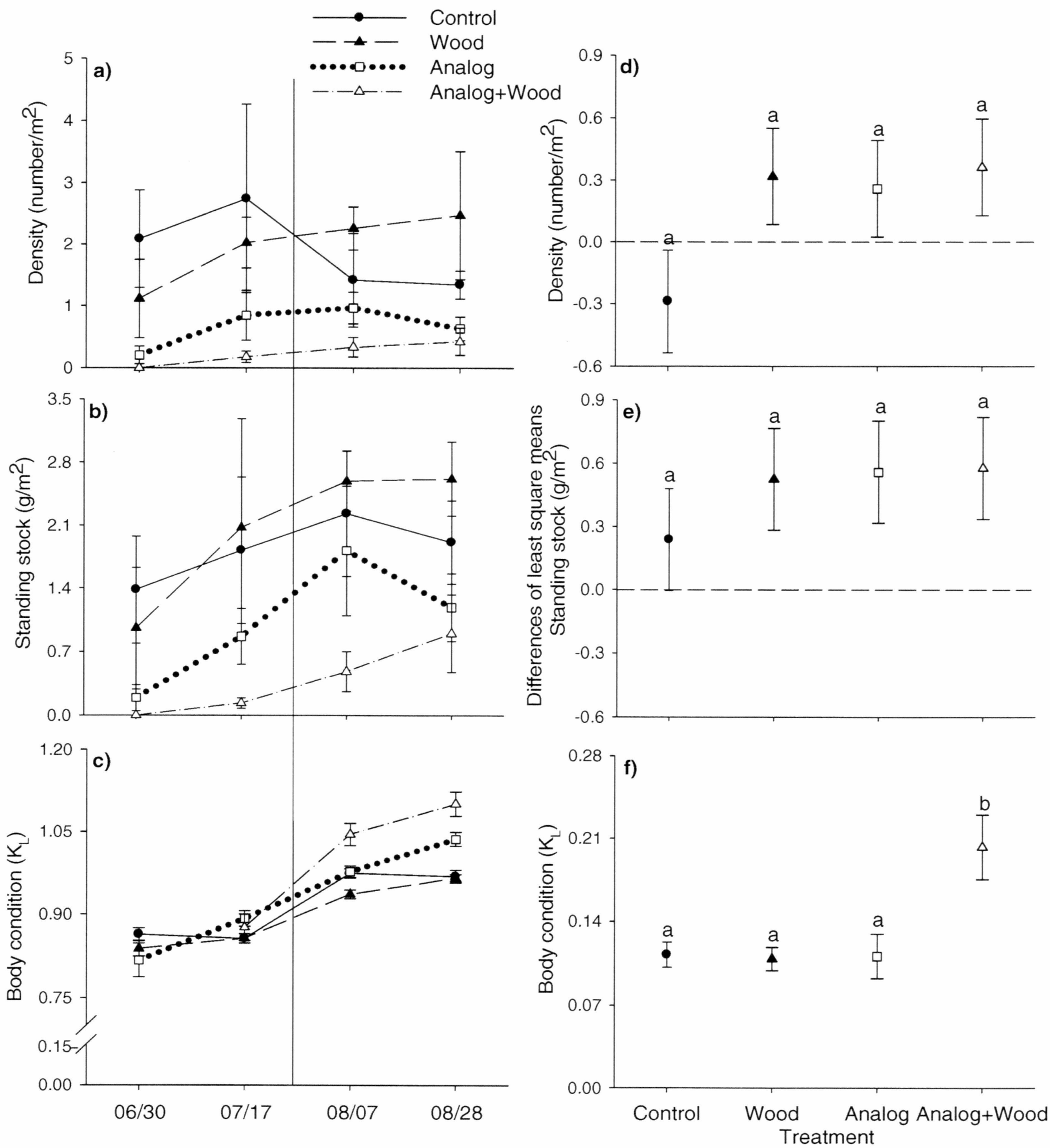


Figure 5.– Coho salmon fry mean density **(a)**, standing stock **(b)**, and condition **(c)** from June to August, and overall treatment differences ($\bar{X}_{after}$ - $\bar{X}_{before}$) of coho density **(e)**, standing stock **(d)**, and condition **(f)**, in response to the four treatments. Solid vertical lines represent treatment application. Error bars indicate ±1 SE. Points without similar letters are significantly different (least-significant-difference mean comparison test, α = 0.05).

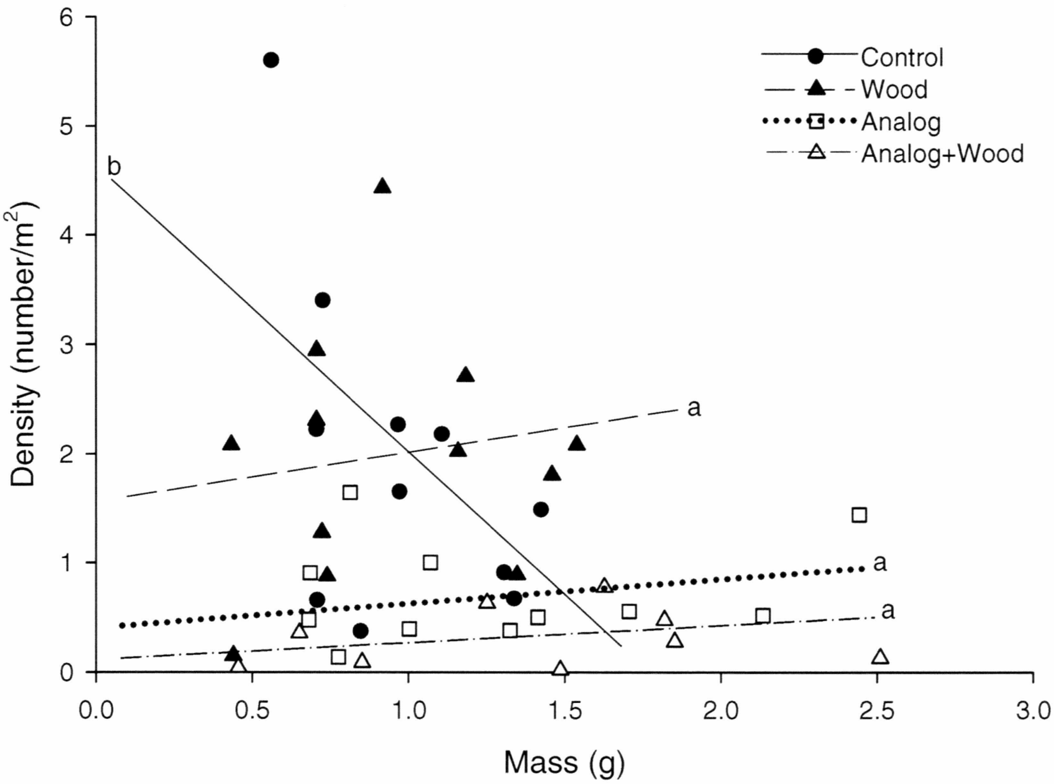
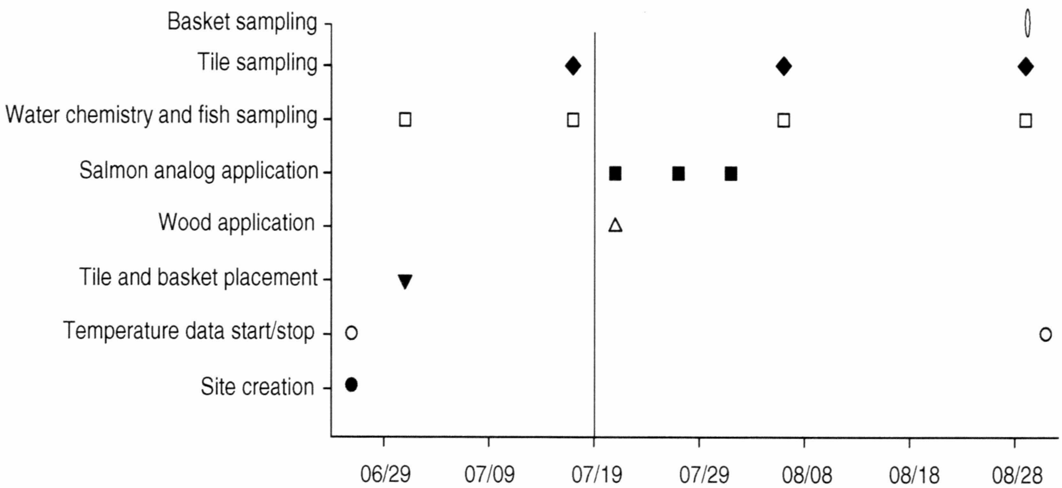


Figure 6.– Relationship between average juvenile coho mass and density for each treatment in alcove habitats on Resurrection Creek, Alaska. Regression lines with different letters have significantly different slopes (t-test, $\alpha = 0.05$).

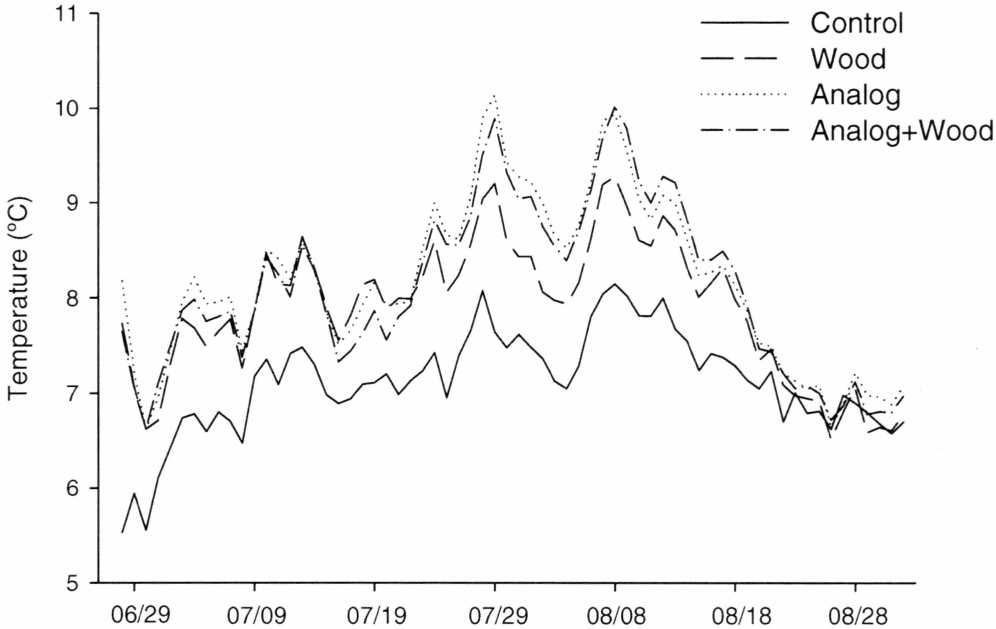
Appendix A.– Habitat characteristics of 10 reference alcoves in an undisturbed reach of Resurrection Creek during a pilot study, June, 2005.

Site #	Alcove area (m^2)	Max depth (m)	Mean water temp. (°C)	Mean conductivity (uS/cm^1)
1.0	39.9	1.2	5.5	58.8
2.0	47.1	0.8	5.7	60.0
3.0	63.6	0.2	6.4	64.8
4.0	46.4	0.4	6.0	69.1
5.0	56.9	0.4	5.4	64.5
6.0	93.9	0.5	6.8	59.1
7.0	71.4	0.3	4.2	52.1
8.0	18.0	0.3	6.3	58.8
9.0	82.3	2.0	6.2	69.1
10.0	10.8	0.3	6.8	73.1
Mean	53.0	0.6	5.9	62.9

Appendix B.– Representative alcove habitat used in this study on Resurrection Creek.



Appendix C.– Timing of events during the 2006 experiment. Solid vertical line indicates end of before treatment addition period.



Appendix D.– Mean temperature of the four treatments from late May to early September, 2006. Each line represents the mean temperature of three replicates for each day.

Appendix E.– Mean concentrations of dissolved nutrients measured over the course of the study in each of the 12 alcoves, 2006.

Site #	Treatment type	TP (mg/L)	Orthophosphate (mg/L)	TN (mg/L)	NH_4^+ (mg/L)	NO_3^- (mg/L)
1	Wood	0.01 (0.004)	0.02 (0.016)	0.21 (0.044)	0.03 (0.018)	0.12 (0.014)
2	Analog	0.86 (0.815)	0.20 (0.157)	1.12 (0.540)	0.30 (0.195)	0.54 (0.361)
3	Control	0.01 (0.001)	<0.01 (0.001)	0.27 (0.066)	0.01 (0.003)	0.09 (0.026)
4	Analog+wood	0.10 (0.056)	0.22 (0.176)	0.79 (0.324)	0.61 (0.427)	0.25 (0.143)
5	Analog	0.42 (0.366)	0.26 (0.211)	2.08 (1.488)	0.63 (0.385)	0.17 (0.075)
6	Wood	0.01 (0.001)	<0.01 (0.001)	0.22 (0.046)	0.01 (0.002)	0.11 (0.014)
7	Control	0.01 (<0.001)	<0.01 (<0.001)	0.30 (0.035)	0.01 (0.002)	0.20 (0.029)
8	Control	0.01 (0.001)	<0.01 (<0.001)	0.19 (0.019)	0.01 (0.004)	0.12 (0.011)
9	Analog	0.01 (0.003)	<0.01 (0.001)	0.21 (0.019)	0.02 (0.005)	0.09 (0.003)
10	Analog+wood	0.05 (0.037)	0.03 (0.022)	0.30 (0.096)	0.07 (0.035)	0.05 (0.011)
11	Wood	0.01 (0.002)	<0.01 (<0.001)	0.20 (0.038)	0.01 (0.002)	0.07 (0.024)
12	Analog+wood	0.08 (0.067)	0.06 (0.051)	0.35 (0.146)	0.09 (0.074)	0.09 (0.007)
Mean	Control	0.01	<0.01	0.25	0.01	0.14
	Wood	0.01	0.01	0.21	0.02	0.10
	Analog	0.43	0.15	1.14	0.31	0.27
	Analog+wood	0.08	0.10	0.48	0.25	0.13
	Overall	0.13	0.07	0.52	0.15	0.16

Note: Standard error (SE) is given after mean in parentheses.

Appendix F.– Mean chlorophyll-*a* standing stock measured June to August, and density and dry mass of invertebrates from artificial substrate baskets sampled on 31 August, 2006.

Site #	Treatment	Mean chlorophyll-*a* standing stock (ug/cm^2)	Invertebrate density ($number/cm^2$)	Invertebrate biomass (mg/cm^2)
1	Wood	0.06 (0.02)	0.94	0.14
2	Analog	0.48 (0.20)	1.78	0.34
3	Control	0.22 (0.02)	1.31	0.27
4	Analog+wood	0.29 (0.16)	0.80	0.22
5	Analog	0.19 (0.09)	0.46	0.12
6	Wood	0.11 (0.06)	0.62	0.12
7	Control	0.08 (0.03)	0.38	0.05
8	Control	0.03 (0.01)	1.20	0.14
9	Analog	0.23 (0.15)	1.30	0.21
10	Analog+wood	0.23 (0.11)	0.06	0.04
11	Wood	0.04 (0.01)	1.39	0.30
12	Analog+wood	0.15 (0.05)	2.12	0.55
Mean	Control	0.11	0.96	0.15
	Wood	0.07	0.99	0.19
	Analog	0.30	1.18	0.22
	Analog+wood	0.22	0.99	0.27
	Overall	0.18	1.03	0.21

Note: Standard error (SE) is given after mean in parentheses.

Appendix G.– Mean juvenile coho density, standing stock, body condition and diet within the four treatments.

Site #	Treatment type	Density (number/m^2)	Standing stock (g/m^2)	Body condition index (K_L)	Diet abundance (number of prey items/fish)	Diet mass (mg/fish)
1	Wood	2.0 (0.4)	3.0 (0.58)	0.94 (0.01)	11.7	1.9
2	Analog	1.0 (0.2)	1.2 (0.28)	0.93 (0.01)	32.3	5.9
3	Control	2.0 (0.2)	2.4 (0.23)	0.91 (0.01)	13.2	2.1
4	Analog+wood	0.2 (0.02)	0.4 (0.05)	0.99 (0.04)	15*	6*
5	Analog	0.6 (0.3)	0.8 (0.72)	0.96 (0.01)	33.3	3.3
6	Wood	1.5 (0.3)	1.6 (0.53)	0.94 (0.01)	14.2	4.7
7	Control	3.5 (1.1)	2.5 (0.32)	0.91 (0.01)	8.3	1.3
8	Control	0.6 (0.1)	0.6 (0.22)	0.94 (0.01)	18.5	0.9
9	Analog	0.4 (0.1)	1.1 (0.31)	1.01 (0.02)	10.2	2.6
10	Analog+wood	0.04 (0.1)	0.6 (0.28)	1.00 (0.03)	23.8	3.3
11	Wood	2.4 (0.9)	1.6 (0.71)	0.89 (0.01)	13.8	1.5
12	Analog+wood	0.4 (0.2)	0.1 (0.32)	1.07 (0.02)	22.7	4.7
Mean	Control	2.1	1.8	0.92	13.3	1.4
	Wood	2.0	2.1	0.92	13.2	2.7
	Analog	0.7	1.0	0.97	25.3	3.9
	Analog+wood	0.2	0.4	1.02	23.3	4.0
	Overall	1.2	1.3	0.96	18.8	3.0

Note: Standard error (SE) is given after mean in parentheses.
* = only one fish sampled